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14. ABSTRACT
Space-based technology is critical to US military and civil capabilities. With technology progression, space-to-space weapons could be fielded in the near future as part of the US arsenal, or as a threat to the US if developed by an adversary. China already has technology that can target spacecraft and could quickly posture for space-to-space combat. The US should perform a cost-benefit analysis to determine which satellites justify the added cost of passive defense measures, then proceed with implementing those defenses. The US should also use a strategy of hedging to develop space-to-space offensive and counterattack weapons. The first priority in hedging should be to develop technology for an explosive kinetic energy parasitic satellite. The second priority should be to develop a power source and improve propulsion technology for use in a high power microwave space-to-space weapon. By beginning preparations now, the US can be equipped not only to defend its interests in space, but to deny adversaries the benefit of space-based assets.

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Executive Summary

Title: Space-to-Space Combat: The Potential for Future Warfare

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Thesis: With the potential for adversaries to engage in space-to-space combat, the United States (US) should protect its interests by employing passive satellite defenses and by hedging for offensive capabilities through space-to-space weapons research and development.

Discussion: Space-based technology is critical to US military and civil capabilities because it supports communications, broadcasting, weather observation, intelligence collection, mapping, navigation, tracking, and targeting. With technology progression, space-to-space weapons could be fielded in the near future as part of the US arsenal, or as a threat to the US if developed by an adversary. Although China publically advocates the peaceful use of space, it already has technology that can target satellites and could quickly posture for space-to-space combat. If space-to-space combat becomes a reality, it could involve weapons that produce a wide variety of effects using kinetic and electromagnetic energy.

Conclusion: The US must prepare for space-to-space combat by better understanding the intent and capability of potential adversaries such as China. It should perform a cost-benefit analysis to determine which of its satellites justify the added cost of passive defense measures, and then proceed with implementing those defenses. Also, the US should use a strategy of hedging to develop space-to-space offensive and counterattack weapons. The first priority in hedging should be to build technology for an explosive parasitic satellite. The second priority should be to develop a power source and improve propulsion technology for use in a high power microwave space-to-space weapon. By beginning preparations now, the US can be equipped not only to defend its interests in space, but to deny adversaries the benefit of space-based assets.

Preface

The United States (US) military and commercial sectors rely heavily on satellite capabilities. Currently, space-faring nations agree that space should be available for peaceful use by all. However, a satellite makes an easy target for a technologically advanced nation. If a nation decides to seize the advantage by attacking another nation's satellites, space could become a domain for combat. The US must consider the possibility of space-to-space combat as it plans for future military capabilities.

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INTRODUCTION

The United States (US) is heavily dependent on satellites, relying on them for capabilities ranging from cell phone calls to early warning of nuclear attack. Satellites' significance to the commercial and military sectors makes them lucrative targets. The ability to attack satellites from the ground, the air, and cyberspace already exists, and technological progress could lead to the ability to attack from space. With the potential for adversaries to engage in space-to-space combat, the US should protect its interests by employing passive satellite defenses and by hedging for offensive capabilities through space-to-space weapons research and development.

This paper focuses on the potential for space-to-space combat. Earth-to-space strike capability already exists and space-to-Earth strike capability is under consideration, but this paper does not address either. Additionally, space weaponization has technical, military, diplomatic, and economic implications that this paper does not consider. For example, it does not reference space situational awareness, which is a military necessity for effective space-to-space combat. It also does not examine the diplomatic matters of space law and treaties, or the economic effects of space weapons research, development, design, manufacturing, launch, and operations.

This paper explains why and how a nation would develop space-to-space combat capability. It begins by briefly discussing the reliance on space-based assets and why those assets make excellent targets. It then describes current Chinese capabilities and indicators that China could pose a threat to US satellites. Next, this paper examines the suitability and feasibility of different types of space-to-space weapons. Then it explains US options for preparing for space-to-space combat, and culminates with a recommendation for specific capabilities.

BACKGROUND

Before discussing *how* a nation would develop space-to-space combat capability, it is important to understand *why* a nation would develop that capability. The same laws of physics that make space the ideal domain for a wide variety of missions also make satellites easy targets. Additionally, with satellites performing critical functions for the military and commercial sectors, they are valuable targets because a few strikes could have a disproportionally large impact on the military or the economy.

Orbits

Space is markedly different from the land, air, or sea. While there are many definitions of space, this paper defines the space threshold at approximately 80 miles above the Earth's surface, the lowest altitude at which a satellite maintains orbit.[1] Space is a harsh environment with atomic oxygen, vacuum, electromagnetic radiation, and charged particles that can degrade a satellite's functionality.[2] Space also has gravity gradients which affect a satellite's motion. The force of gravity is inversely proportional to the square of the distance between the satellite and the center of the Earth, meaning the gravitational pull toward Earth decreases quickly as a satellite's altitude increases.[3]

Gravity is a critical component of orbital mechanics. Without gravity, a satellite travels in a straight line unless another force acts on it, such as propulsion. With gravity, a satellite orbits the Earth in a relatively consistent path. This occurs because the satellite's velocity vector is parallel to a line tangent to the Earth, but gravity pulls the satellite toward the center of the Earth, which prevents it from travelling away from the Earth along its velocity vector. As gravity pulls the satellite toward Earth, the Earth's surface curves away, allowing the satellite to continuously "fall" toward Earth, as shown in Figure 1.

When a satellite is launched into a specific orbit, it stays in that orbit unless it employs a significant propulsive force to move to another orbit, or until atmospheric drag degrades the orbit. Unlike a vehicle travelling in air or water where fluid mechanics allow control surfaces to produce agile movements, a vehicle in space does not have similar maneuverability.

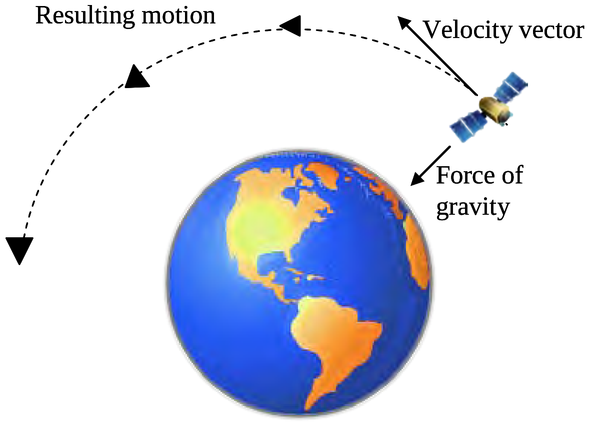

Figure 1: Orbital motion

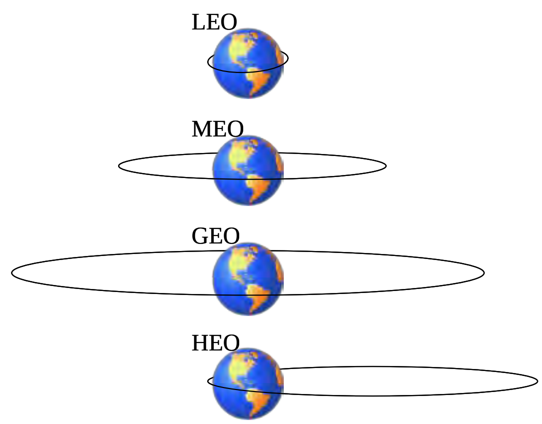

Figure 2: Orbital realm examples

A satellite's speed relative to the Earth depends on its altitude and its mechanical energy, not on its mass, size, or shape.[4] As its altitude increases, a satellite's speed decreases. There are four basic orbital realms characterized by altitude: low Earth orbit (LEO), medium Earth orbit (MEO), geosynchronous orbit (GEO), and highly elliptical orbit (HEO), as shown in Figure 2.

LEO altitudes range from approximately 80 to 620 miles. Satellites in circular LEO orbits have velocities ranging approximately from 17,510 to 16,450 miles per hour, meaning they orbit the Earth every 1.4 to 1.7 hours.[5] MEO altitudes range from approximately 620 to 22,235 miles, with approximate corresponding circular orbit velocities of 16,450 to 6,880 miles per hour, meaning MEO satellites orbit the Earth every 1.7 to 23.9 hours. GEO is a special orbit with an altitude of 22,236 miles and a position approximately over the equator. Satellites in GEO have a velocity of 6,878 miles per hour, meaning they orbit the Earth exactly once per day

and therefore appear nearly stationary as viewed from a point on Earth. HEO, as the name suggests, are orbits with pronounced elliptical shapes, coming within hundreds of miles of the Earth at the lowest point of the orbit and travelling tens of thousands of miles away from the Earth at the opposite point. Satellites in HEO have varying velocities with increased speeds close to the Earth and decreased speeds farther away.

There are infinite orbits within the four orbital realms, each characterized by precise orbital elements that define its size, shape, tilt, swivel, orientation, and position.[6] A satellite's orbital realm and orbital elements depend on its function. For example, certain communications satellites are in GEO for consistent area coverage and for the high altitude that allows them to "see" approximately one-third of the Earth. Imaging satellites are in LEO to keep them close to the Earth for better resolution and have tilted orbits so they cover a range of latitudes. Satellites providing services to northern latitudes are in tilted HEO orbits to maximize their usability.

Reliance on Space

Space has certain advantages over the land, air, and sea. For example, it is the ultimate high ground, allowing satellites to "see" large areas of the Earth, which is useful for many broadcasting and data collection missions. Another advantage of space is over-flight access to restricted regions, which is critical for collecting intelligence from areas that are not otherwise accessible. Varying orbital periods are another benefit, allowing LEO satellites to cover much of the globe in a brief time and GEO satellites to have persistent coverage of a specific region.

The space domain's benefits are widely recognized with at least 26 countries operating satellites.[7] There are over 3,200 satellites in space, and United States Strategic Command's Joint Space Operations Center reports that approximately 1,100 of those satellites are currently operational.[8] These satellites have scientific, civil, and military applications. Scientific missions

focus on exploration and experimentation. Civil applications impact nearly every facet of modern life including cell phones, cable television, weather forecasts, navigation, tracking, and mapping. Military applications include communications, broadcasting, weather observation, intelligence collection, navigation, tracking, and targeting. The military also uses commercial satellites to augment its capabilities. For example, approximately 90 percent of US military communications use commercial satellites.[9]

Space-based technology is pervasive in the US military. Operation DESERT STORM was the US military's first large-scale use of space assets, and its reliance on space has increased steadily since then. For example, it not only uses the Global Positioning System for highly accurate navigation and tracking, but also for guiding weapons ranging from gravity bombs to cruise missiles.[10] It has multiple satellite communications constellations to pass large amounts of mission-critical data. Also, the military uses the Defense Support Program to detect enemy missile launches and nuclear detonations. While space is clearly militarized, it is not yet weaponized, meaning space assets support, but do not conduct, combat operations.

Satellites as Targets

A satellite's vulnerability makes it a logical target. Attackers can accurately predict its location due to a relatively constant orbit and maneuverability limitations. Additionally, it is a complex and delicate system, making it highly susceptible to damage. While commands to a damaged satellite might be able to reconfigure it for operations, there is virtually no on-orbit physical repair capability. Also, procuring, launching, and initializing a satellite is expensive and time consuming, so a damaged or disabled satellite is not readily replaced.

An adversary could significantly degrade a nation's military capability with a few coordinated attacks on satellites. An attack on US intelligence, communications, and positioning

satellites could decrease the US military's advantage in land, air, sea, and cyber warfare.[11] Since the US military is reliant on space assets, security analysts generally agree that an adversary will attack the space segment.[12] Another benefit of targeting a satellite is that the attack could potentially be anonymous, leaving an adversary with little fear of retribution.[13]

The US, China, Russia, the United Kingdom, France, Germany, Italy, Japan, and Israel have technological and industrial bases that could develop weapons to attack satellites.[14] Of these nations, only the US, China, and Russia have a proven ability to target satellites. From the late 1960s through the early 1980s, Russia demonstrated the ability to intercept a satellite with another satellite, damage a satellite using an air-launched interceptor, and blind satellite optics using ground-based directed energy weapons.[15] However, it has not shown its ability to target satellites in recent decades, possibly indicating a decline in capability or interest. China, on the other hand, is expanding its satellite attack capabilities.

CHINESE CAPABILITY

China developed its space program at a staggering rate. The program began just 2 decades ago and China can now build and launch its own satellites, conduct manned spaceflight missions, and target other nations' satellites.[16] With a proven ability to disable, degrade, and destroy other satellites using ground- and air-based assets and ambitions to expand its space program, it is reasonable to expect that China will consider developing space-to-space combat technology. While the US is seeking a cooperative relationship with China, China's increasing military strength and lack of publicized military intent is a cause for concern.[17]

China's Public Stance

China has spoken out against weaponizing space. It is a leader in the Conference on Disarmament and has pushed for a treaty to prohibit weapons in space.[18] According to its

National Space Administration, "China is unflinching in taking the road of peaceful development" of space technology.[19] To support its opposition of space weaponization, China made the point that attacks in space could result in debris that would threaten other spacecraft.[20] This statement is ironic because China is responsible for more than 14% of all the space debris that the US tracks.[21] It is unclear if China's advocacy for peaceful space is altruistic or to protect its own satellites.

China's Current Capabilities

China is one of the most space-capable nations in the world. In the early 1990s, it purchased Russian hardware and training to start its space program.[22] Since then, China has developed a strong space program in its own right and is rapidly improving its capabilities.[23] With the US and Russia, it is one of three nations capable of manned spaceflight.[24] China is also one of six nations capable of launching satellites, matching the number of successful US launches in 2010 and exceeding it in 2011.[25] It has approximately 70 satellites in orbit for experimentation, communications, data relay, intelligence collection, weather surveillance, Earth observation, and navigation.[26] Its navigation constellation is expected to provide nation-wide coverage of the People's Republic of China in 2012 and global coverage in 2020.[27] Additionally, China is one of nine nations with the industrial and technological capability to develop space weapons.[28]

China currently has multiple ground-based directed energy offensive counterspace capabilities. In 2005, it reportedly tested its satellite jamming capability.[29] It has also reportedly used a laser to blind optics on US and French satellites.[30]

China also has ground-based kinetic energy offensive counterspace capability. In 2007, it used a ground-launched medium-range ballistic missile as an anti-satellite weapon (ASAT) to

destroy one of its old LEO weather satellites.[31] Although China publicly stated that space weapons should be prohibited because of the debris they create, its ASAT created approximately 3,000 pieces of debris in an area occupied by 125 satellites.[32] In 2011, a piece of debris from China's ASAT came close to hitting the International Space Station, forcing the station's crew to take shelter in an escape capsule.[33]

In 2010, China demonstrated another kinetic capability by launching two missiles for an exo-atmospheric collision.[34] This was more technologically difficult than the 2007 ASAT demonstration, indicating that China continues to improve its capabilities.[35] Also in 2010, China conducted rendezvous maneuvers between two satellites.[36] This technology could be intended for space station docking, or it could be for a co-orbital ASAT, which is a satellite in orbit near a target satellite.

With China advocating peaceful use of the space domain but actively developing assets with offensive counterspace capabilities, its intentions are unclear. One explanation is that China's offensive counterspace capabilities are intended to deter adversaries that rely on space-based assets from pursuing conflict.[37] Another explanation is that the technology demonstrations are part of a test and evaluation plan to prepare for space-to-space combat. The US Department of Defense expects China to seek asymmetric ways to counter US military strength, so attacking US satellites could be part of China's strategy.[38]

China's Intent for the Future

China has expressed long-term dedication to developing space-based capabilities, but keeps specific plans under close-hold.[39] In a white paper published in 2000, its Information Office of the State Council stated that China would increase space development for the next 20 years.[40] Indeed, infrastructure and talent to support China's space industry have increased since

2000, indicating a commitment to advancing its space programs.[41] Whether those programs will be peaceful or aggressive remains to be seen.

In a Chinese military text published in 2005, a People's Liberation Army major general said China should initiate offensive space operations to achieve space superiority because that is the first step in gaining air, sea, and ground supremacy during war.[42] Recent US Air Force research indicates that China desires space warfare capability, but does not yet have the necessary skills or organizational construct.[43] It is possible that China's long-term goal is to use the space domain as another battlefield and its current public aversion to space weaponization is because it is not ready for space-based combat.

Strategically, China sees information superiority as the basis for overall battlefield superiority, and according Chinese military space analyst Senior Colonel Li Daguang, space dominance is necessary for information dominance.[44] To achieve space dominance, China believes offensive space operations should include attacks on enemy space and ground segments and the data links connecting them, and should be persistent to prevent regeneration.[45] People's Liberation Army documentation specifically addresses the importance of destroying or disabling enemy reconnaissance and communications satellites.[46] China sees defending its own satellites as another step toward space dominance and advocates defenses including maneuvering, camouflage, stealth, hardening, shielding, and autonomous operations.[47] Also, China believes it can shape enemy actions through deterrence operations that include exercising, deploying, and employing space forces.[48]

China's research and development efforts indicate preparations for future attacks on satellites. A Chinese study determined its future space surveillance should be able to detect and track objects as small as 4 inches across that are up to 311 miles away.[49] This would allow

China to track potential target satellites in a variety of orbits. Reports indicate that China is pursuing space weapons development using laser, microwave, and cyber attacks.[50] It is also refining the ASAT technology it used to shoot down its weather satellite in 2007.[51] Additionally, China has shown interest in US satellite payload computers, which could be an indication of an attempt to identify vulnerabilities in US satellites that it could target.[52]

WEAPONS FOR SPACE-TO-SPACE COMBAT

With satellites as easy and lucrative targets and at least one potential adversary demonstrating anti-satellite technology, the path to space-to-space combat seems to be developing. US research during the Cold War on space-based weapons for ballistic missile defense opened the door to examining other types of space-based weapons.[53] Using space-based weapons to attack satellites has the advantages of not needing on-demand launches and not sending a weapon through the atmosphere, but also has disadvantages.

Space-to-Space Weapons Disadvantages

One disadvantage of space-to-space weapons is that immediate satellite strike capability is unlikely. The weapon must come in view of an antenna to receive the strike command, which could take seconds or hours depending on the data relay architecture and the weapon's position and orbit. A robust communications architecture minimizes the time to command the weapon and is technologically feasible, but could be cost prohibitive. Maneuvering into position to attack could take minutes or weeks depending on the obits of the target and the weapon and the weapon's available thrust. A large constellation of space-based weapons, possibly numbering in the thousands, increases the likelihood of a short maneuver time, but could be too expensive.[54]

Another disadvantage of space-to-space weapons is the propellant requirement for maneuvering, which increases cost and decreases longevity. The amount of thrust a propulsion

system can generate impacts how quickly the weapon can perform orbital maneuvers, and the propulsion system's efficiency impacts how much propellant the weapon must carry. The three general types of space propulsion are chemical, nuclear, and electric, and as their names indicate, they use different means of producing an exhaust stream to move the satellite. Most space propulsion is chemical because it produces the most thrust, but it is also the least efficient and therefore uses the most propellant. Nuclear propulsion is three times more efficient than chemical propulsion, but is inappropriate for many kinetic weapons because it could create radiation belts in space. Electrical propulsion's thrust is four to seven orders of magnitude smaller than chemical propulsion, but its efficiency can be more than three orders of magnitude higher.[55] Electric arcjets and ion thrusters, both types of electrical propulsion, were used as early as the 1990s to produce small thrust for minor positional corrections.[56] If propulsion technology matures, space-based weapons could have sufficient thrust for orbital maneuvers without the propellant requirements that make launch and longevity impractical.

Vulnerability to attack is another disadvantage of space-to-space weapons. Like the satellites the weapon targets, it has the same vulnerabilities of a predictable orbit, limited maneuverability, and fragile components. Also, unlike ground-, air-, and sea-based weapons systems, a space-based weapon does not have home turf where it can take refuge.

Kinetic Weapons

Space-to-space weapons fall into two basic categories: kinetic and electromagnetic. A kinetic weapon relies on a mass with a velocity to impact a target satellite and either damage it or alter its course. The extent of damage or course change depends on the physical characteristics and velocities of the mass and its target. The mass' velocity relative to the target depends on the angle at which the mass approaches the target, and could be greater than 35,000 miles per hour.

One benefit of a space-to-space kinetic energy weapon is that the extremely high velocities allow a small mass to have enormous kinetic energy. To put the destructive potential in perspective, consider the fact that a 1 pound mass travelling at just 6,710 miles per hour has the equivalent effect of 1 pound of high explosive.[57]

One drawback of a kinetic energy weapon is that its high velocity makes approaching and intercepting the target satellite difficult. First, space surveillance systems must determine the target satellite's exact orbital parameters. Then, the weapon's orbit must be precisely calculated. Finally, the weapon must accurately apply thrust to follow the prescribed path.

Another disadvantage is that a kinetic energy weapon is likely to create debris upon impacting the target satellite. Each piece of debris is in orbit and can become a threat to non-target satellites. In LEO, a piece of debris the size of a marble has the same energy as a 1 ton block dropped from a five story building on Earth.[58] Even a fleck of paint in orbit can damage a satellite upon impact.[59]

Although there are drawbacks to kinetic energy space-to-space weapons, there are also advantages based on the specific type of weapon. One type of kinetic energy space-to-space weapon is a projectile that intercepts a target satellite. A benefit of a space-to-space interceptor is that it is not a significant technological leap. Like China, the US has shown the ability to intercept a target satellite using an ASAT launched from within the Earth's atmosphere.[60] Additionally, although the US' Brilliant Pebbles program did not reach maturation, it showed there were no technical issues to developing a space-based antimissile interceptor.[61] A space-to-space projectile could build on ASAT and Brilliant Pebbles technology.

Another type of kinetic energy space-to-space weapon is space mines, analogous to land or sea mines. They are inert objects in a target satellite's path that inflict damage from the

impact velocity, or explosives that use proximity detectors to detonate when the target satellite is near, sending shrapnel to tear into the target satellite. Space mines could be positioned near the target well ahead of the time for attack. Ideally, the adversary would not be able to detect the mines, requiring a size and shape to elude space surveillance.

Unless space mines are delivered as inert systems, power and station keeping are technological hurdles. Using solar arrays for power requires large surfaces that increase the risk of detection. However, space mines could use solar arrays in GEO because they would be too far from Earth-based space surveillance to be detected. Batteries are an alternative power source, but have a limited life. An operational issue for space mines is station keeping because the target satellite's minor orbit adjustments as well as orbital decay would need to be detected and then the mines would need to match those changes to maintain proximity to the target.[62]

Another kinetic energy space-to-space weapon a capsule that releases pellets in the vicinity of the target. At orbital velocities, a cloud of pellets could significantly damage the target satellite.[63] A pellet weapon requires similar technology as a projectile interceptor, but less positional precision since proximity, not interception, is the goal.

A microsatellite, which is a small satellite generally weighing less than 200 pounds, can be a kinetic energy weapon by impacting a target satellite to damage it or nudge it into another orbit. The US has been developing microsatellite technology for years and China is reportedly experimenting with microsatellite weapons, although this is not confirmed beyond Chinese press reports.[64] A microsatellite weapon could require the same targeting precision as projectile interceptors and the same low observability as space mines.

Another use of a microsatellite as a kinetic space-to-space weapon is as a parasitic satellite. A parasitic satellite attaches to a target satellite and then uses various means to disrupt

or destroy its functionality, such as propulsion to push it off course or an explosion to damage it. The benefit of a parasitic satellite is that once it attaches to the target satellite, it does not need to maneuver to maintain proximity to the target. However, a parasitic satellite has drawbacks. It requires immensely precise maneuvering to attach to a target satellite without moving the target in a way to indicate to the target satellite operator that it docked. Also, if used in LEO, it requires a low-observable design to remain undetected.

Electromagnetic Weapons

A space-to-space electromagnetic weapon uses a stream of photons with the same wavelength to damage or destroy satellite components. One benefit of an electromagnetic weapon is that the photons travel at the speed of light, which is over 160,000 times faster than the average bullet.[65] The photons are also not constrained by orbital mechanics and propulsion limitations.

One type of electromagnetic weapon is a nuclear device that generates an electromagnetic pulse (EMP). An EMP's immediate effect is a nuclear radiation pulse of X-rays, gamma rays, ultraviolet rays, and neutrons that travels omnidirectionally from the blast source.[66] For a satellite in its line of sight, the pulse damages electronics, structure, and coatings. Its effective range depends on its yield and its detonation altitude.[67] An EMP's long-term effect is a radiation belt of high-energy electrons trapped in the Earth's geomagnetic field.[68] As a satellite travels through the belt, it can experience surface coating damage and harmful electrostatic discharge.[69] An EMP's effectiveness against satellites was shown in 1962 when the US detonated the STARFISH nuclear device at an altitude of approximately 250 miles. Of the 21 satellites in orbit, the STARFISH EMP degraded or ended the mission of 8, and the effects on the remaining 13 are not publically available.[70]

The main drawback of an EMP weapon is that it is nondiscriminatory, creating immediate and long-term threats for enemy and friendly satellites. Another drawback is that an adversary can protect its critical satellites from many of the EMP's effects through hardening techniques.

Another category of electromagnetic weapons is directed energy weapons, which unlike an EMP, create a stream of photons that have the same direction.[71] Jammers, lasers, and microwaves are all directed energy weapons. A directed energy weapon's effects are scalable and range from interrupting signals needed for operations to physically destroying satellite components.[72] Also, its effects can be temporary or permanent.

The drawbacks of a directed energy weapon are primarily based on the levels of available technology. As energy travels, it decreases proportionally to the inverse of the range squared.[73] Therefore, delivering sufficient energy to affect a distant target could require power on the order of megawatts.[74] With current technology, producing that level of power requires equipment that is too large to be used in space.[75] Directing the energy is also difficult, requiring equipment that could be prohibitively large for space basing.[76] Also, a directed energy weapon has a cumulative effect, so a sustained attack could be necessary, making precise aiming more difficult.[77]

One type of directed energy weapon is a jammer that transmits a signal with the same frequency as the signal it intends to block, but at higher power to overwhelm the target signal. There are three types of satellite communications that can be jammed: uplink, downlink, and crosslink. The uplink sends data, including commands, from the Earth to the satellite. The downlink sends telemetry and mission data from the satellite to the Earth. The crosslink sends data between satellites. Jamming uplink and crosslink signals could inhibit mission performance, interfere with satellite navigation, and degrade satellite health.[78] Jamming

downlink and crosslink signals could result in lost mission and state of health data and the inability to determine appropriate commanding. In addition to signal interference, a jammer could have enough power to overheat target satellite components, creating physical damage.[79]

A drawback of a space-based jammer is that it can be easily located and targeted for attack because it transmits a signal.[80] Another disadvantage of space-based jamming is the power requirement because the jamming signal loses strength as it travels. Decreasing the distance between the jammer and the receiver decreases the power requirement, but maintaining that positioning can be difficult. Keeping a jammer between the signal source and the receiver puts it in a different orbit than the target satellite, meaning it has a different velocity. To create an uninterrupted jamming signal, the jammer must maneuver constantly, or a constellation of jammers must be used.[81] To decrease maneuvering, the jammer could be in the same orbit as the target and use the target's antenna side lobes, which are areas outside of the target satellite antenna's intended reception area that can still pick up certain signals. However, side lobe shape can be designed to make jamming through a side lobe less likely.[82] An additional jamming issue is that target satellites have many design options to overcome jamming, such as highly directional receivers, tight frequency bands, and filters.[83]

Another directed energy tactic similar to jamming is spoofing. Spoofing also targets a specific frequency with high power to swamp the intended signal, but spoofing transmits a legitimate signal whereas jamming transmits noise.[84] The implications of spoofing are serious. Uplink spoofing could allow an enemy to control the target satellite, and downlink spoofing could convince satellite operators that the satellite is doing something that it really is not. Spoofing is much more difficult than jamming because it requires detailed knowledge of the target satellite and the data it sends and receives. Encryption can effectively prevent spoofing.[85]

Lasers are another possibility for a space-to-space directed energy weapon. Lasers are electromagnetic radiation with wavelengths on the order of nanometers.[86] The small wavelength results in very little diffraction, allowing a laser beam to effectively target a satellite hundreds of miles away.[87] Laser energy causes heat damage to a target satellite and is especially effective against fragile components, such as solar cells.[88] The US demonstrated a laser's effectiveness by shooting down rockets, artillery shells, and mortars in testing.[89] While these tests used a ground-based laser and targets within the atmosphere, they demonstrated a laser's destructive power.

One difficulty with a space-based laser is its size. To be a useful weapon, a laser must be high-powered, on the order of kilowatts or megawatts, which requires equipment that is currently prohibitively large for space.[90] A laser also needs optics to focus and aim the beam. To effectively target a satellite approximately 1,860 miles away, a laser needs a mirror with a 33 foot diameter; for a satellite 18,640 miles away, the mirror needs a 325 foot diameter. [91] Fielding mirrors that large is impossible today. Another difficulty with a space-based laser is keeping the beam incredibly steady because even a small perturbation can cause it to miss a distant target and perhaps inadvertently hit a friendly satellite. Beam control is especially difficult for a chemical laser because it is powered by combustion, which causes vibrations.[92]

A variant of a space-based laser weapon is a ground-based laser that uses a space-based mirror to direct the beam at a target satellite.[93] The mirror removes the atmospheric distortion from the beam and then reflects it toward the target.[94] While this still requires a mirror that is prohibitively large by today's standards, it does not require a large space-based power source. In the 1990s, the US Air Force generated a laser beam on the ground, bounced it off a space-based mirror, and hit a spot on the Earth.[95] While the target was not space-based, this did prove the feasibility of using a space-based mirror as a laser beam relay.

Another space-to-space weapon that uses a laser is a dazzler, which swamps a target satellite's optical sensors with light.[96] Dazzling is generally a temporary effect, but with enough intensity, a dazzler could permanently blind an imaging satellite by damaging the detectors and electronic connections.[97] One of the difficulties with a dazzler is it needs to use a frequency bands that the target satellite does not filter out, requiring knowledge of the target satellite's specifications.[98] Also, the dazzler needs to remain in position to swamp the optical sensors, which could be difficult or impossible depending on duration and orbits.

A high power microwave is another option for a space-to-space directed energy weapon. Microwaves are electromagnetic radiation with wavelengths on the order of centimeters or millimeters.[99] They diffract more than lasers due to larger wavelengths, and therefore can only effectively target a satellite less than a mile away.[100] A microwave can enter a target satellite through its receiver if it is in the frequency range the receiver accepts. A benefit to this method of entry is the target satellite's communications system amplifies the microwave.[101] Due to its large wavelength, a microwave can also enter a satellite through seams in its skin.[102] Once inside, a microwave's effects range from minor processor disruptions to total destruction of electronics.[103] Another benefit of a high power microwave is that it is delivered via a short pulse, so the source does not need to maintain its position relative to the target satellite.[104]

As with lasers, one drawback of a space-based high power microwave is that it requires a large amount of power generated by equipment that is too large for space basing, especially if the microwave enters the satellite through gaps and seams and not through the communications system. Another consideration is that the size of the gap determines the frequency that can enter through it, so a high power microwave weapon must generate a range of frequencies to increase the likelihood of penetrating the target satellite.[105]

Another space-to-space directed energy weapon is a parasitic satellite. Like a kinetic energy parasitic satellite, a directed energy parasitic satellite attaches to a target satellite. It then uses means to disrupt or destroy the target satellite's functionality, such as jamming, laser, or high power microwave attacks.

UNITED STATES' OPTIONS

With a variety of directed energy and kinetic energy weapon possibilities, the US has many options in posturing for space-to-space combat. However, it must first decide whether preparing for space-to-space combat is in line with its policies and goals. If the US determines that it should begin preparations, it must determine if its strategy will be defensive, offensive, or a combination of the two. It must also decide if it intends to implement that strategy now, or when a threat emerges.

United States' Public Stance

In 2001, the Rumsfeld Commission, which was formed to determine how space projects could impact US security, released its findings. It determined that the US was more reliant on space-based assets than any other nation and warned that it was "an attractive candidate for a 'Space Pearl Harbor'." The commission recommended the US be able to deter and, if necessary, defend against threats to US space assets.[106]

Today, the US policy echoes the Rumsfeld Commission's recommendations. The US National Space Policy advocates all nations having peaceful space access and encourages transparency in space activities. However, it states that the US will "deter, defend, and if necessary, defeat" attempts to obstruct or attack its space-based assets.[107] While the US policy does not commit to developing space-to-space weapons, it does not exclude that possibility.

Offense Versus Defense

The US National Space Policy indicates a need for a mix of defensive and offensive capabilities. In examining purely space-to-space capabilities, the US has many options. With indications that China could weaponize space, examining defensive capabilities is a natural course of action. The US should implement defensive capabilities for the satellites it cannot afford to lose or replace.

The US Air Force defines defensive space control as operations that protect friendly space capabilities from intentional and unintentional threats.[108] An intentional threat is an enemy targeting an asset or a capability, and an unintentional threat ranges from the natural space environment to second- and third-order effects from planned operations. Defensive measures to counter these threats can be passive or active.

Passive defense, as defined by the US Department of Defense, is an action to reduce the probability and extent of damage without seizing the initiative.[109] One passive defense measure is to make a satellite difficult for an enemy space surveillance system to locate by using a low-observable design.[110] Maneuvering is also a passive defense technique, although orbital mechanics make large-scale, rapid maneuvering difficult. Another passive defense is hardening, which decreases damage from kinetic impacts and electromagnetic radiation, but increases cost.[111] There are numerous hardening techniques, including constructing the satellite from damage-resistant materials, shielding electronics, and using filters to separate and block harmful signals.[112] For satellites with optics, adding shutters to the optics is a passive defense to protect against dazzling and blinding.[113] An additional passive defense is system redundancy, so if a particular component is damaged or destroyed, the satellite can switch to a redundant component and continue operations.

Active defense is attacking to defend space assets.[114] According to the US Department of Defense, active defense includes limited offensive operations and counterattacks.[115] According to the US Air Force, the effects on enemy capabilities could be temporary or permanent and range from disruption to destruction.[116]

Any space-based kinetic energy or electromagnetic weapon could be used for active defensive operations as well as offensive operations. Offensive space-to-space operations prevent an adversary from using a space-based capability.[117] The US Department of Defense argues offensive space control is necessary to negate an enemy's space capability that could put the US, its allies, and its coalitions at risk.[118]

Deterrence is a strategy that combines defensive and offensive space-based capabilities. According to the US Department of Defense, deterrence prevents enemy attack because a counterattack capability exists or the cost of the attack is too high.[119] In a deterrence strategy, the US could develop space-to-space weapons to convince an enemy that an attack will be countered. Also, the US could build satellite defenses to convince an enemy that an attack will be ineffective. The US already uses rhetoric as part of a deterrence strategy by stating that it will repay attacks on its satellites however, whenever, and wherever it desires, leaving the door open for space-based attacks, conventional military attacks, and economic and political reprisal.[120]

When to Weaponize

Designing and building a satellite takes years, and developing the technology that satellite uses could take decades. Therefore, if the US anticipates needing space-to-space weapons in 10, 20, or 30 years, it should start development today. However, satellites, which generally do not have the cost-reducing benefit of mass production, are extremely expensive. Also, technology, especially computing technology, progresses rapidly, so developing a satellite

today that might not be needed for decades means it would be far from cutting-edge by the time it is in use. To avoid a large expense for an outdated capability, the US should not commit to actually designing a space-to-space weapon until the need for that capability exists.

Hedging is an option between designing a specific space-based weapon now and waiting until the weapon is actually needed to begin development. Hedging is a risk mitigation technique that focuses on research and development now, as opposed to design, to enable rapid system development in the future.[121] It allows the US to prepare for the worst by building critical technology, but does not design a complete system prematurely.[122]

RECOMMENDATION

First, to prepare for the future, the US must better understand possible threats. It needs to collect and analyze intelligence on potential adversaries' space programs, including the extent of military involvement and the technological and industrial bases. While the intelligence community and military are closely linked, understanding threats in the space domain also requires strong partnership with various sectors of the technical community.

The US must not underestimate China's current capabilities or its ability to quickly develop new threats. Developments in China's space industry occur rapidly, and its discretion in revealing its intent could leave the US little time to react to a Chinese realization of space-to-space combat capability. The US must adopt a proactive approach, but not an overreactive approach, in preparing to counter a space-to-space attack.

The US must analyze the benefit of adding passive defenses to its satellites for some degree of protection from future threats. Shielding electronics, adding signal filters, and making critical subsystems redundant improve survivability using currently-available technology, but also increase procurement and launch costs. Through a cost-benefit analysis, the US military and

commercial sectors must determine which satellites merit the costs and add defensive measures to those satellites.

Finally, the US should use a strategy of hedging, meaning it should develop space-to-space weapons technology now but not incorporate the technology into satellite designs until space-to-space combat appears imminent. In choosing what technology to develop, the US must consider that many weapons for offensive actions and defensive countermeasures are better suited for ground-basing than space-basing. For example, large kinetic energy interceptors and EMP weapons can be launched from Earth, eliminating the costs of space basing, without losing effectiveness. Also, jammers, lasers, and dazzlers can effectively target satellites from Earth, and ground basing negates the problem of equipment that is too large for space basing.[123]

As part of its hedging strategy, the US should develop technology for explosive parasitic satellites. While this could require improving docking ability, decreasing component size, and increasing battery life, those advancements are more readily feasible than the advancements required for many other types of space-based weapons discussed in this paper. Also, the ability to attach explosives to adversaries' satellites that can be detonated at will would give the US a huge advantage in shaping the battlefield. As part of a longer-term hedging strategy, the US should also develop technology for high power microwave weapons, which requires reducing the power source size and developing space propulsion for faster and more efficient maneuvering. Decreasing the power source size necessitates a leap in technology, but has the potential to benefit not only space-to-space combat, but also ground, air, and sea combat.

CONCLUSION

Space-based technology is critical to US military and civil capabilities because it supports communications, broadcasting, weather observation, intelligence collection, mapping,

navigation, tracking, and targeting. With technology progression, space-to-space weapons could be fielded in the near future as part of the US arsenal, or as a threat to the US if developed by an adversary. Although China publically advocates the peaceful use of space, it already has technology that can target satellites and could quickly posture for space-to-space combat. If space-to-space combat becomes a reality, it could involve weapons that produce a wide variety of effects using kinetic and electromagnetic energy.

The US must prepare for space-to-space combat by better understanding the intent and capability of potential adversaries such as China. It should perform a cost-benefit analysis to determine which of its satellites justify the added cost of passive defense measures, and then proceed with implementing those defenses. Also, the US should use a strategy of hedging to develop space-to-space offensive and counterattack weapons. The first priority in hedging should be to build technology for an explosive parasitic satellite. The second priority should be to develop a power source and improve propulsion technology for use in a high power microwave space-to-space weapon. By beginning preparations now, the US can be equipped not only to defend its interests in space, but to deny adversaries the benefit of space-based assets.

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